

# Non-activated transport of strongly interacting two-dimensional holes in GaAs

Jian Huang,<sup>1</sup> D. S. Novikov,<sup>1</sup> D. C. Tsui,<sup>1</sup> L. N. Pfeiffer,<sup>2</sup> and K. W. West<sup>2</sup>

<sup>1</sup>*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA*

<sup>2</sup>*Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974, USA*

We report on the transport measurements of two-dimensional holes in GaAs field effect transistors with record low densities down to  $7 \times 10^8 \text{ cm}^{-2}$ . Remarkably, such a dilute system (with Fermi wavelength approaching  $1 \mu\text{m}$ ) exhibits a non-activated conductivity that grows with temperature approximately as a power law at sufficiently low temperatures. We contrast it with the activated transport found in more disordered samples and discuss possible transport mechanisms in this strongly-interacting regime.

PACS numbers: 73.40.-c, 73.20.Qt, 71.27.+a

The question of how a strong Coulomb interaction can qualitatively alter an electronic system is fundamentally important. It has generated great interest in studying the transport in two-dimensional (2D) electron systems.<sup>1</sup> Since the interaction becomes effectively stronger with lower 2D electron density, samples with most dilute carriers are desirable to probe the interaction effects. As the density is lowered, strong enough disorder can localize the carriers so that the interaction effect is smeared by the insulating behavior. Therefore, a clean 2D environment is vital to uncover the underlying interaction phenomena.

For a long time, the dilute 2D carriers have been known as insulators characterized by activated conductivity. Specifically, in an Anderson insulator,<sup>2,3</sup> the conductivity follows the Arrhenius temperature dependence  $\sigma \sim e^{-E_g/k_B T}$ , where  $E_g$  is the mobility edge with respect to the Fermi level. The energy relaxation due to phonons in the impurity band results in a softer exponential dependence  $\sigma \sim e^{-(T^*/T)^\nu}$ , realized via the variable-range hopping (VRH) process.<sup>4,5</sup> Here, the exponent  $\nu = 1/3$  for non-interacting electrons,<sup>4</sup> while  $\nu = 1/2$  if the Coulomb gap opens up at the Fermi level.<sup>5</sup> Finally, strong Coulomb interactions are believed to crystallize the 2D system<sup>6</sup> which then can become pinned by arbitrarily small disorder. A relation  $d\sigma/dT > 0$ , being a natural consequence of the activated transport, eventually became a colloquial criterion of distinguishing an insulator from a metal.<sup>7</sup>

The experimental results in the dilute carrier regime are known to be greatly influenced by the sample quality, which has much improved over time. The phonon-assisted hopping transport was observed in early experiments.<sup>7</sup> As the sample quality improved, the later experiments performed on 2D electrons in cleaner Si-MOSFETs demonstrated that the temperature-dependence of the resistivity  $\rho = \sigma^{-1}$  can be either metal-like ( $d\rho/dT > 0$ ), or insulator-like ( $d\rho/dT < 0$ ), depending on whether the carrier density  $n$  is above or below a critical value  $n_c$ .<sup>8</sup> On the insulating side, where  $n < n_c$ ,  $\rho(T)$  grows exponentially with cooling.<sup>9</sup> Similar results have since been observed in various low disorder 2D systems, and the resistivity on the insulating side has

been consistently found to follow an activated pattern  $\rho \sim e^{(T^*/T)^\nu}$ , with  $\nu$  varying between  $1/3$  and  $1$ .

In this work, we focus on the transport properties of clean 2D holes in the dilute carrier regime where the insulating behavior is anticipated. To achieve high quality and low density, we adopt the GaAs/AlGaAs heterojunction insulated-gate field-effect transistor (HIGFET) where the carriers are only capacitively induced by a metal gate.<sup>10,11,12</sup> Because there is no intentional doping, the amount of disorder is likely to be less, and the nature of the disorder is different from that of the modulation-doped samples. Previous experiments on similar 2D hole<sup>12,13</sup> HIGFET devices have demonstrated a non-activated transport. The temperature dependence  $\sigma(T)$  of the conductivity becomes approximately linear,  $\sigma \propto T$ ,<sup>13</sup> when the density is lowered to a minimum value of  $1.6 \times 10^9 \text{ cm}^{-2}$ . However, it is unclear whether the linear  $T$ -dependence will persist for lower densities or it is a crossover to a different transport regime.

We have measured several high quality  $p$ -channel HIGFET samples. The hole density  $p$  in our devices can be continuously tuned to as low as  $p = 7 \times 10^8 \text{ cm}^{-2}$ , in which case the nominal Fermi wavelength  $\lambda_F = (2\pi/p)^{1/2} \simeq 0.95 \mu\text{m}$ . Our main finding is that the conductivity  $\sigma(T)$  of the cleanest samples decreases with cooling in a non-activated fashion for densities down to  $7 \times 10^8 \text{ cm}^{-2}$ . The temperature dependence of the conductivity appears to be best approximated by a non-universal power-law  $\sigma \propto T^\alpha$  with  $1 \lesssim \alpha \lesssim 2$ . The systematic analysis of this dependence will be published elsewhere.<sup>14</sup> At base temperature, the magnitude of  $\sigma$  is much greater than that of a typical insulator with similar carrier density. Our results point at the presence of the delocalized states in the system with a record low carrier density. Thus our system is not an insulator even though  $d\sigma/dT > 0$ .

The device geometry is a standard  $3 \text{ mm} \times 0.8 \text{ mm}$  Hall bar. The measurements were performed in a dilution refrigerator with a base temperature of  $35 \text{ mK}$ . At each value of the gate voltage, the mobility and density were determined through measuring the longitudinal resistivity  $\rho$  and its quantum oscillations in the magnetic field. The temperature dependence of the resistivity was mea-

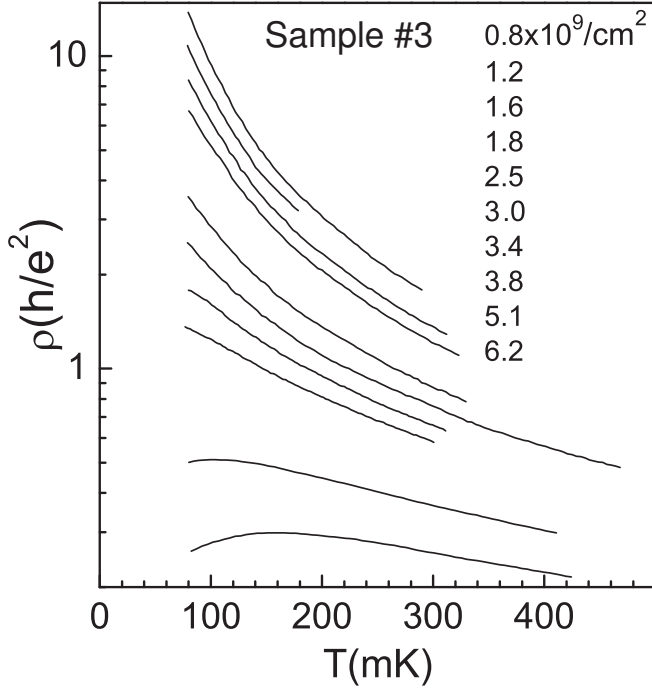


FIG. 1: Temperature dependence of the resistivity of sample #3 in semi-log scale for a set of specified hole densities listed on the righthand side.

sured with an ac four-terminal setup at high carrier density, while both ac and dc setups were used for the low-density high-impedance cases. To ensure linear response, current drive as small as 1 pA was used during the measurements at the lowest carrier density. Driving currents of different amplitudes were used for the low density cases and the measured resistivity did not change with varied current drive.

The temperature dependence of the resistivity  $\rho(T)$  for a number of hole densities from sample #3 is shown in Fig. 1, with lowest temperature of 80 mK. At first glance, the density dependence of the  $\rho(T)$  curves is similar to that found around the metal-to-insulator transition,<sup>7</sup> with  $p_c = 4 \times 10^9 \text{ cm}^{-2}$  being the critical density. For  $p > p_c$ , the system exhibits the apparent metallic behavior ( $d\rho/dT > 0$ ) at sufficiently low temperatures. The downward bending of  $\rho(T)$  becomes weaker as  $p$  approaches  $p_c$ , and disappears for lower  $p$ . The derivative  $d\rho/dT$  at low  $T$  then becomes negative, a conventional characteristic of an insulator,<sup>7</sup> for the whole temperature range. At the transition, the resistivity is of the order of  $h/e^2$ . The value of  $p_c$  is very close to that obtained in a similar device in Ref. 12.

Fig. 2 shows the conductivities  $\sigma(T)$  of the same sample (#3) for the corresponding densities. For  $1.8 \times 10^9 \text{ cm}^{-2} < p < 3.8 \times 10^9 \text{ cm}^{-2}$ , the conductivity increases approximately linearly with  $T$  at high temperatures (above  $\sim 200 \text{ mK}$ ). The linear regions are almost parallel for different densities, similar to that observed previously.<sup>12,13</sup> This linear dependence occurs at temper-

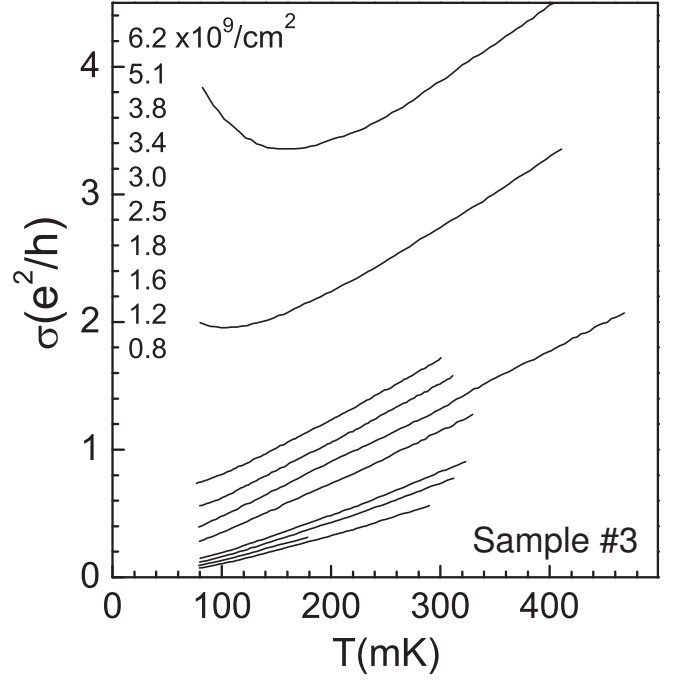


FIG. 2: Re-plot of the data from Fig. 1 in terms of conductivity vs. temperature.

atures above the nominal Fermi temperature and will be studied in detail elsewhere.<sup>14</sup> However, for lower densities, from  $8 \times 10^8 \text{ cm}^{-2}$  to  $1.8 \times 10^9 \text{ cm}^{-2}$ , the conductivity deviates from the linear decrease at low temperatures.  $\sigma(T)$  exhibits a slower change with  $T$  as the density is reduced, with weaker  $T$ -dependence close to the base temperature. The conductivity values ( $\sim 0.1e^2/h$ ) are considerably larger than those found in the more disordered sample which will be described later.

In Fig. 3, we compare the measured conductivities with the VRH predictions according to Mott<sup>4</sup> and to Efros and Shklovskii<sup>5</sup> for sample #3 [panels (a) and (b)], and sample #4 [panels (c) and (d)]. The hopping conductivity  $\sigma \sim e^{-(T^*/T)^\nu}$ , repeatedly observed in previous experiments on the insulators, is expected to occur at low temperatures. However, in both of our samples, the conductivity is approximately linear (in the semi-log scale) at high temperatures but nonlinear at low temperatures. It clearly deviates from the VRH law (dotted lines), for both  $\nu = 1/3$  [panels (a) and (c)] and  $\nu = 1/2$  [panels (b) and (d)]. The increasing deviation with cooling indicates that the temperature dependence is weaker than activated. The deviation is slightly larger for the E-S ( $\nu = 1/2$ ) case.

The qualitative difference in the temperature dependence between our clean samples from more disordered samples (previously measured) is apparent in the log-log scale plot in Fig. 4. Here, the conductivity from a more disordered sample (#6) is also included for comparison. For about the same densities ( $7 - 8 \times 10^8 \text{ cm}^{-2}$ ), the dependence  $\log \sigma$  versus  $\log T$  for the two clean-

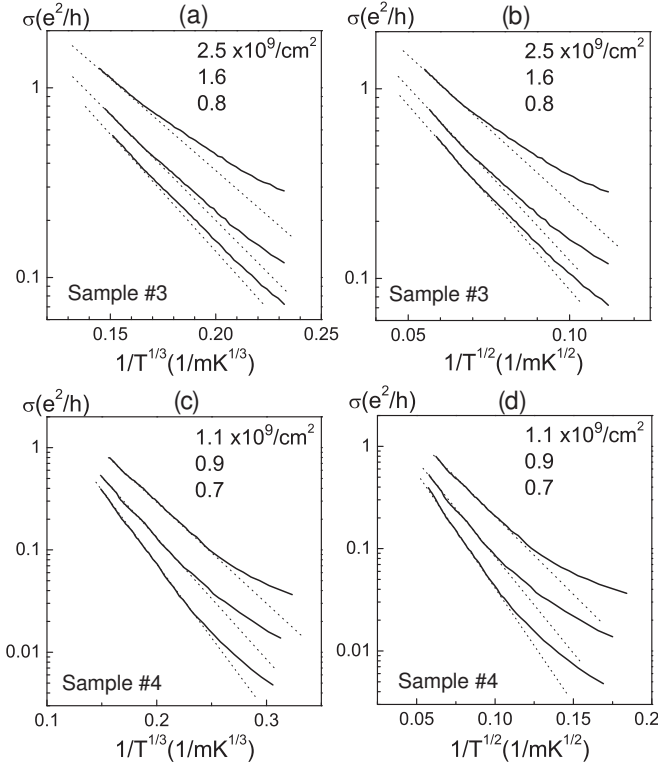


FIG. 3: Comparison of the conductivities  $\sigma(T)$  with VRH transport models: (a), (c) Mott; (b), (d) Efros-Shklovskii. Panels (a) and (b) are results from sample #3, and (c) and (d) are from sample #4.

est samples appears to be approximately linear below 150 mK, indicating a power-law-like relationship  $\sigma \propto T^\alpha$ . The exponent  $\alpha$ , which corresponds to the slope in the plot, is  $\alpha \simeq 2.2$  for  $p = 7 \times 10^8 \text{ cm}^{-2}$  and  $\alpha \simeq 1.6$  for  $p = 8 \times 10^8 \text{ cm}^{-2}$ . Both numbers differ from the much lower values previously observed in carrier densities around  $1.6 \times 10^9 \text{ cm}^{-2}$ .<sup>11,13</sup> The trend, larger  $\alpha$  for lower density, is consistent with the results in Ref. 11. On the other hand, the conductivity for the more disordered sample (#6) exhibits a clear downward diving, consistent with the activated behavior. Note that the low- $T$  conductivity in the more disordered sample is at least three orders of magnitude smaller than that in the clean ones for the same carrier density.

The insulating character of our more disordered sample is consistent with previously observed Anderson insulators in lower quality 2D systems. However, our clean HIGFET results show that, with less disorder, the transport becomes non-activated, indicating the presence of delocalized states.

What is responsible for the apparent delocalization? The Anderson localization, being an interference effect, can occur only when the system is sufficiently phase-coherent. At finite temperature, strong electron-electron interaction can dramatically reduce the coherence length  $l_\phi$ . As the carrier temperatures in our case are of the order of the Fermi temperature  $T_F$ , there is no suppression

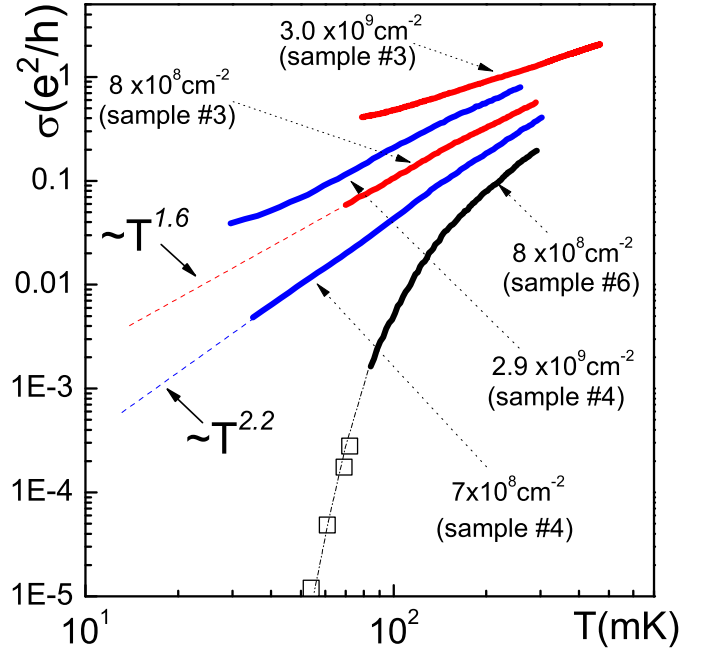


FIG. 4: Power-law  $\sigma(T)$  behavior from clean samples, samples #3 and #4, in comparison with the activated behavior found in a more disordered sample (#6). The scattered points in the graph are the DC results of sample #6.

of the interaction between the quasiparticles associated with the filled Fermi sea. In this situation it is plausible to assume that  $l_\phi \sim \lambda_F$ .<sup>15</sup> On the other hand, the 2D localization length  $\xi$  is exponentially sensitive to the amount of disorder.<sup>16</sup> Thus it seems likely for the phase coherence to be broken on the scale  $l_\phi < \xi$  in our clean samples, while the opposite is true for the more disordered one.

The transport mechanism that leads to the observed temperature dependence  $\sigma(T)$  remains unknown. Moreover, even the nature of the ground state of such a system is unsettled.<sup>17,18,19,20</sup> Below we show that the electron-electron interactions are extremely strong at short distances, and decay relatively fast at larger distances due to the screening by the metallic gate. This nature of interaction between the delocalized carriers suggests that the holes form a strongly-correlated liquid.

We now consider the electron-electron interaction in more details. In HIGFETs, the metallic gate at distance  $d$  from the 2D hole layer screens the  $1/r$  interaction down to  $1/r^3$  when  $r \gtrsim 2d$ . In our case,  $d = 600 \text{ nm}$  for sample #3 and  $d = 250 \text{ nm}$  for sample #4.

The short-distance  $1/r$ -interaction is indeed very strong. If treated classically as a one-component plasma, the interaction parameter  $\Gamma = E_C/k_B T \sim 100$ , corresponding to an enormous Coulomb energy  $E_C = e^2/\epsilon a \sim 10 \text{ K}$ , with  $\epsilon = 13$ . Since the temperature in our system is of the order of the Fermi energy,  $E_F = \hbar^2/ma^2 \sim 100 \text{ mK}$ , quantum effects may also be important. A standard estimate of the strength of interac-

tion is the quantum-mechanical parameter  $r_s = a/a_B$ , where  $a_B = \hbar^2\epsilon/mc^2$  is the Bohr radius. It requires the knowledge of the band mass  $m$  that has never been measured in such a dilute regime. Higher density cyclotron resonance measurements give  $m \simeq 0.2 - 0.4 m_e$ ,<sup>21</sup> whereas low-density theoretical estimates (based on the Luttinger parameters)<sup>22</sup> give  $m \simeq 0.1 m_e$ . The  $r_s$  value for  $p = 1 \times 10^9 \text{ cm}^{-2}$  is in the range of 25 – 100 for the mass range of  $m = 0.1 m_e - 0.4 m_e$ .

The long-distance dipolar interaction is relatively weak for such low densities since the  $1/r^3$  potential is short-ranged in two dimensions. Therefore, the liquid is favored over the Wigner crystal (WC),<sup>18</sup> as the quantum fluctuations ( $\sim 1/r^2$ ) overcome the  $1/r^3$  interaction. Meanwhile, even for a classical system, the 2D WC melting temperature  $T_m \simeq E_C/130k_B$  is already low<sup>23</sup>:  $T_m = 56 \text{ mK}$  for  $p = 1 \times 10^9 \text{ cm}^{-2}$ . The screening further

reduces<sup>24</sup>  $T_m$  to make the WC even harder to access. The absence of the pinned WC in our samples is corroborated by the non-activated transport in the linear response regime and the absence of singularity in  $\sigma(T)$ .

In summary, we have observed a non-insulating behavior in the putatively insulating regime for the hole densities down to  $7 \times 10^8 \text{ cm}^{-2}$ . Our results suggest that the 2D holes form a strongly-correlated liquid whose properties require further investigation.

This work has benefited from valuable discussions with I.L. Aleiner, B.L. Altshuler, P.W. Anderson, R.N. Bhatt, and M.I. Dykman. We also thank Stephen Chou for the use of the fabrication facilities. The work at Princeton University is supported by US DOE grant DEFG02-98ER45683, NSF grant DMR-0352533, and NSF MRSEC grant DMR-0213706.

- 
- <sup>1</sup> T. Ando, A.B. Fowler, and F. Stern, *Rev. Mod. Phys.* **54**, 437 (1982).
  - <sup>2</sup> P.W. Anderson, *Phys. Rev.* **109**, 1492 (1958).
  - <sup>3</sup> E. Abrahams, P.W. Anderson, D.C. Licciardello, and T.V. Ramakrishnan, *Phys. Rev. Lett.* **42**, 673 (1979)
  - <sup>4</sup> N.F. Mott, *J. Non-Cryst. Solids* **1**, 1 (1968).
  - <sup>5</sup> B.I. Shklovskii and A.L. Efros, *Electronic Properties of Doped Semiconductors*, Springer-Verlag, Berlin (1984).
  - <sup>6</sup> B. Tanatar and D. M. Ceperley, *Phys. Rev. B* **39**, 5005 (1989).
  - <sup>7</sup> E. Abrahams, S.V. Kravchenko, and M.P. Sarachik, *Rev. Mod. Phys.* **73**, 251 (2001).
  - <sup>8</sup> Kravchenko, S. V., G. V. Kravchenko, J. E. Furneaux, V. M. Pudalov, and M. D'Iorio, *Phys. Rev. B* **50**, 8039 (1994).
  - <sup>9</sup> W. Mason, S. V. Kravchenko, G. E. Bowker, and J. E. Furneaux, 1995, *Phys. Rev. B* **52**, 7857
  - <sup>10</sup> B. E. Kane, L. N. Pfeiffer, and K. W. West, *Appl. Phys. Lett.* **67**, 1262 (1995).
  - <sup>11</sup> M. P. Lilly, J. L. Reno, J. A. Simmons, I. B. Spielman, J. P. Eisenstein, L. N. Pfeiffer, K. W. West, E. H. Hwang, and S. Das Sarma, *Phys. Rev. Lett.* **90**, 056806 (2003).
  - <sup>12</sup> Hwayong Noh, M. P. Lilly, D. C. Tsui, J. A. Simmons, E.H.Hwang, S.Das Sarma, L. N. Pfeiffer, and K. W. West, *Phys. Rev. B* **68**, 165308 (R) (2003).
  - <sup>13</sup> Hwayong Noh, M. P. Lilly, D. C. Tsui, J. A. Simmons, L. N. Pfeiffer, and K. W. West, *Phys. Rev. B* **68**, 241308 (R) (2003).
  - <sup>14</sup> Jian Huang *et al.* cond-mat/0610320 (2006).
  - <sup>15</sup> B.N. Narozhny, G. Zala, and I.L. Aleiner, *Phys. Rev. B* **65**, R180202 (2002)
  - <sup>16</sup> A. MacKinnon and B. Kramer, *Phys. Rev. Lett.* **47**, 1546 (1981); D. Vollhardt and P. Wölfle, *Phys. Rev. Lett.* **48**, 699 (1982).
  - <sup>17</sup> S. Das Sarma and E. H. Hwang, *Phys. Rev. B* **68**, 195315 (2003).
  - <sup>18</sup> B. Spivak, S. Kivelson, cond-mat/0510422 (2005).
  - <sup>19</sup> B. Spivak and S. A. Kivelson *Phys. Rev. B* **70**, 155114 (2004).
  - <sup>20</sup> B. Spivak, *Phys. Rev. B* **67**, 125205 (2003).
  - <sup>21</sup> Pan W, Lai K, Bayrakci SP, Ong NP, Tsui DC, Pfeiffer LN, West KW, *Appl. Phys. Lett.* **83**, 3519 (2003).
  - <sup>22</sup> R. Winkler, *Spin-orbit coupling effects in two-dimensional electron and hole systems* (Springer, New York, 2003).
  - <sup>23</sup> D.S. Fisher, B.I. Halperin, and R. Morf, *Phys. Rev. B* **20**, 4692 (1979).
  - <sup>24</sup> P. Hartmann, G.J. Kalman, Z. Donkó, and K. Kutasi, *Phys. Rev. E* **72**, 026409 (2005).